Sense-making across Disciplines: Physical Models, Theoretical Frameworks, and the Connections between Education in the Humanities and Sciences

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Abstract: Across disciplines, the fundamental goal of authentic learning is sense-making: making sense of the world around us, our interactions, and art. As education shifts from a discipline focused on propagating knowledge as 'stuff' to a focus on propagating understanding and teaching the means towards understanding, the learning of sense-making practice across the disciplines is becoming more important. In the recent past, education at nearly all levels has focused on the teaching of facts. The practices of experts within disciplines were taught rarely, if at all, and almost exclusively at the level of domain-specific skills. However, sense-making practices are surprisingly universal, and not just across the sciences. In this paper, I discuss the parallels between the sciences and humanities with respect to the practice of sense-making, specifically the mental/physical models in the sciences and the theoretical frameworks deployed in the social sciences and the humanities. I will make the case that we should begin addressing in our classrooms the cross-cutting nature of the practices of all learners, so that students can see how what they are doing when analysing history is not epistemologically dissimilar to their physics class.

Keywords: sense-making; models; theoretical framework; science practice

Across disciplines, the fundamental goal of authentic learning is sense-making: making sense of the world around us, our interactions, and art. Sense-making goes beyond content knowledge. For example, when studying history, knowing when and where something happened is necessary but insufficient to the understanding of why and how. Knowing science facts, like the shape and location of the mitochondria is necessary but insufficient to the understanding of its role in the cell. Knowing and identifying plot structures is necessary but insufficient to the understanding of the author's message or the work's place in culture. Knowing in general is necessary but insufficient to understanding.[1]

As education shifts from a discipline focused on propagating knowledge as 'stuff' to a focus on propagating understanding and teaching the means towards understanding, the learning of sense-making practice across the disciplines is becoming more important. In the recent past, education at nearly all levels has focused on the teaching of facts.[2] The practices of experts within disciplines were taught rarely, if at all, and almost exclusively at the level of domain-specific skills. However, sense-making practices are surprisingly universal, and not just across the sciences.

This paper will discuss the parallels between the sciences and humanities with respect to the practice of sense-making: mental/physical models in the sciences and the theoretical frameworks deployed in the social sciences and the humanities. In particular, I will discuss the universal theory of learning called 'situated cognition,' and its application to multiple disciplines, including science. In particular, we will look at how modelling and testing in science parallels building and using frameworks in other disciplines, and how the sharing of effective teaching strategies across the arts/science divide could be beneficial for everyone. To this end, I will discuss my science education group's work on teaching science practice with respect to modelling and how integrating practice with context/content leads to understanding and knowing within the context of situated cognition. Specifically, I shall describe and demonstrate the teaching theory called 'cognitive

1 J. Greeno, 'Gibson's affordances', Psychological Review, 101 (1994) 336–42.

2 J.C. Moore, Creating Scientists: Teaching and assessing science practice for the NGSS (New York, 2017), 22.

apprenticeship,' and show how this framework for teaching can be used across disciplines to develop broader sense-making abilities.

When focusing on the practices of science that are universal, the learner begins to make the connections between disciplines and see investigation as a universal process for truth-seeking as opposed to a context-depended means to learning facts within a tiny domain. Their entire epistemology changes, and this which we have found is fundamental for students making the novice-expert transition.[3] I shall make the case that we should go one step further and begin addressing in our classrooms the cross-cutting nature of the practices of all learners, so that students can see how what they are doing when analysing history is not epistemologically dissimilar to their physics class.

Situated cognition: a theory of learning

Situated cognition is a learning theory that assumes all knowledge is situated in actions that occur within cultural, social, and physical contexts.[4] In simpler language, knowledge is inseparable from doing. More importantly, knowledge cannot be separated from the means in which the knowledge is learned by the community that 'knows' it. In our case, situated cognition tells us that students can only understand science or humanities ideas if they understand how the practice of the practitioner leads to those ideas.

What does it mean 'to understand' a topic. Within the framework of situated cognition, three fundamental components combine within the learner's mind to form a deep understanding: (1) content knowledge, (2) practice abilities, and (3) appropriate reasoning to link the practice to the knowledge.[5] These three components can be considered the three legs of a stool: remove one leg, and the stool falls down. Similarly, the

3 3 J.C. Moore, Creating Scientists: Teaching and assessing science practice for the NGSS (New York, 2017), 22. Students to Think More Like Scientists', European Journal of Physics Education, 3 (2012), 1–12.

4 J. Brown, A. Collins, and P. Duguid, 'Situated Cognition and the Culture of Learning', Educational Researcher, 18 (1989), 32.

5 J.C. Moore, Teaching science thinking: developing scientific reasoning in the classroom (New York, 2018); D. Kuhn, 'What is scientific thinking and how does it develop?', in Blackwell Handbook of Childhood Cognitive Development, ed. U. Goswami (Malden, 2014), 371–93.

absence of either component within some context results in a lack of true understanding of that context. The learner may know facts, but without the underlying context of how those facts came to be known, and the thinking required to link actions to knowing, the learner does not understand the content that they know.

For example, if we tell a small child that the stove is hot and will burn her, does that child now understand the concepts of heat and burning? They might not touch the stove because they were told not to, but they have not truly developed an understanding without also learning how the knowledge that 'stove equals danger' came into being. In this instance, we have separated the knowledge from the process of gaining the knowledge. Similarly, in the context of science, we can tell students that the mitochondria is the battery of the cell. The students can then repeat this on an examination and label it properly on a diagram. However, do those students now truly understand what the mitochondria is and does? Students of literature may be taught and therefore know that the green light in F. Scott Fitzgerald's The Great Gatsby is a symbol for the 'American dream' broadly, and the character Gatsby's hopes and dreams for the future specifically. However, do students necessarily understand literary symbols and their construction, identification, and interpretation?

Situated cognition tells us that true knowing does not happen without action. How can the learner find out what the mitochondria does? What evidence can they draw on? Specifically, what actions does the expert perform that lead to knowledge about the mitochondria? How does the learner interpret symbols? Can they do so in a new context unaided? What actions does the expert perform that lead to appropriate identification and interpretation? Fundamentally, situated cognition tells us that understanding is a verb, not a noun, as opposed to theories of knowledge as accumulated stuff in our brains.

In the USA, situated cognition as a fundamental framework for learning has been incorporated within national standards across disciplines. With respect to the sciences, the Next Generation Science Standards (NGSS) are a set of national suggestions based on the USA National Research Council's report A Framework for K-12 Science Education: Practices, Crosscutting Concepts, and Core Ideas.[6]

6 National Research Council, A Framework for K-12 Science Education: Practices, Crosscut-

Specifically, the NGSS tightly integrates science practice, reasoning, and science content. As examples of this tight integration of content with action, I present the following excerpts from the NGSS student-performance expectations:

Students who demonstrate understanding can

1. construct an argument supported by empirical evidence to support … [content]
2. develop a model based on evidence to illustrate … [content]
3. conduct an investigation to provide evidence that … [content]

The general formula for all performance expectations within the NGSS is as follows: students who demonstrate understanding … can perform science practice … in pursuit of content. A similar pattern in seen in new standards in the USA across disciplines, as reflected in the Common Core Standards Initiative.[7]

Situated cognition says that students can only understand ideas if they understand how to practice in context. Merely 'knowing' some fact does not in itself signify understanding, no more than being able to repeat that the stove is hot signifies understanding of hotness. Students learn science by doing science. Students learn historical analysis by doing historical analysis. Students learn art by doing art. This theory of learning leads to the obvious theory of teaching: you teach students science by teaching them how to do science and then having them do it. This is what we call cognitive apprenticeship, and it is the polar opposite of teaching-by-telling.

A cognitive apprenticeship and making connections across disciplines

In a traditional apprenticeship the apprentice learns processes through physical integration into the practices associated with the content area.[8] As an example from my own past, I once trained as an electrician's apprentice before going to university. I worked side-by-side with a

ting Concepts, and Core Ideas (Washington, D.C., 2012); NGSS Lead States, 'Standards by DCI' in The Next Generation Science Standards: For States, By States (Washington, 2013).

7 National Governors Association Center for Best Practices, Common Core State Standards (Washington, D.C., 2010).

8 D. Pratt, Five perspectives on teaching in adult and higher education (Ann Arbor, MI, 1998).

professional master electrician who showed me the trade. I learned by watching an expert, then doing electrical work under his supervision. As I gained more and more abilities, the master electrician allowed me more and more freedom to work until I was eventually practising on my own.

Cognitive apprenticeship borrows from traditional apprenticeship as an applied teaching technique for students constrained to the classroom. Research across many different disciplines has shown that simulating expert-like practice in context and in an aided environment can increase student abilities in an unaided setting.[9] For example, when we teach science in the classroom using cognitive apprenticeship as a framework, we are really doing what is called 'simulated' apprenticeship. Instead, if we get students involved in real science explorations, such as working in a research laboratory on a university campus or research centre under the direction of a professional scientist, then students are doing what Barb and Hay loosely describe as 'science at the elbows of experts'.[10]

The principal teaching methods of cognitive apprenticeship are modelling, coaching, scaffolding, reflection, articulation, and exploration.[11] For modelling, a subject expert explicitly demonstrates a task to the student. The student is able to build a conceptual model for the task. Once students have developed a conceptual model, the expert observes them attempting a task and gives them feedback and assistance at critical moments (coaching). Assistance is slowly withdrawn as students gain new abilities and can manage more of the task on their own (scaffolding). Reflection and articulation serve to internalize the student's observations and experience, as well as aid in integrating new knowledge and problem-solving abilities. Finally, exploration fosters independence and encourages autonomous problem formulations and solutions. In a proper exploration, students can set their own goals and develop their own testing strategies, all of which fosters independent learning.[12]

9 A. Ghefaili, 'Cognitive apprenticeship, technology, and the contextualization of learning environments', Journal of Educational Computing, Design, and Online Learning, 4 (2003).

10 S. Barab and K. Hay, 'Doing science at the elbows of experts: Issues related to the science apprenticeship camp', Journal of Research in Science Teaching, 38 (2001), 70–102.

11 A. Collins, J. Brown, and A. Holum, 'Cognitive Apprenticeship: Making Thinking Visible', American Educator, 6 (1991), 38–46.

12 B. Larkins, J. Moore, L. Rubbo, and L. Covington, 'Application of the cognitive apprenticeship framework to a middle school robotics camp', in SIGCSE 2013 – Proceedings of

Sense-making in the sciences: models and observations

For an example of an apprenticeship-based scaffolded learning process within the framework of situated cognition, I shall now discuss a brief activity designed to develop sense-making abilities in the sciences, in young children. In particular, I will show you an example of leading a learner through the process of building a basic mental model for light. Models are representations of the physical world that allow the scientist to understand and predict future behaviour. A mental model is a representation of physical reality within the learner's mind that assists with understanding, specifically concepts that have no obviously visible exemplars, such as light. (We can't 'see' a light ray directly!) A physical predictive model is a more sophisticated formal model that can be used to make predictions. Models in general are typically approximations of the real world and can consist of diagrams, an analogy, a mathematical equation, and/or a simulation on the computer. Students of science must learn how to develop models through observations and how to use models to make predictions. Note that the focus is on the action of developing and using models within a context, which is a necessary condition for understanding within our framework.

The representation in Figure 1a is based on the mental model called 'the ray model of light'. Built into this representation is also a physical model of light reflection that predicts how light 'rays' will reflect off mirrors. These models for light may or may not automatically align with the mental model in the student's mind. Within the framework discussed above, we want students to not only learn about the ray model, but also learn how models are developed and how to use them. Therefore, we will want to look at activities that guide students toward building a ray mental model from the ground up, where students are ultimately the creators of the model. Basically, students will create and then use the same representation shown in Figure 1a, however, they will understand not only what the picture represents, but how such representations are created in the first place. They will have learned content and practice.

the 44th ACM Technical Symposium on Computer Science Education (Denver, CO, 2013), 89–94.

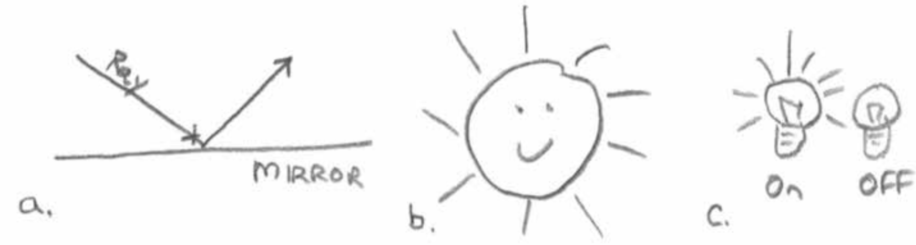

Fig. 1. (a) Representation for the ray model of light and reflection off a plane mirror; (b) a drawing of the sun consistent with drawings by primary school children; and (c) using a ray model of light to indicate in representative form that a light bulb is on

Cognitive apprenticeship has us model, coach, and scaffold instruction in expert-like practices, but we still have to answer an important question: how do we teach mental model building? We start here, because learners cannot possibly begin making sense of their world until they have first built a mental model for it.[13] Foundationally, students will build a mental model for light, often subconsciously, long before instruction, and that model may not conform to the model of the expert.[14] So there are two issues that we face: (1) dealing with the potentially erroneous model, and (2) building a new one. In Seymour Papert's constructionist learning students are guided through activities where they must construct their own mental models of the world around them, using information they already know to 'construct' new knowledge.[15] This means rather than teach-by-telling where the model is just provided, often in opposition to the well-formed model already in the student's head, we want students to build models based on their own experiences and observations.

Even students at the beginning of primary education already have a fairly sophisticated ray model that they use in their minds when thinking about light. Imagine asking a young child to draw a picture of the sun. More than likely, most of the students in the class will draw a picture similar to that shown in Figure 1b which shows a picture of the

13 G.E. Box, 'Robustness in the strategy of scientific model building', in Robustness in Statistics, ed. R. Launer and G. Wilkinson (New York, 1979).

14 R.M.J Byrne, and P.N. Johnson-Laird, '"If" and the problems of conditional reasoning', Trends in Cognitive Sciences, 13 (2009), 282–7.

15 K. Alesandrini, and L. Larson, 'Teachers bridge to constructivism', The Clearing House, 75 (2002), 118–21.

sun produced by a primary-school student in the USA. Interestingly, I get essentially the same pictures whether I am working with a group of elementary school children, college physics majors, or in-service teachers from around the world. In constructionist pedagogy, this pre-existing mental framing of the sun will be used as a starting point for building a mental model for light.

Figure 1c shows a student-drawn picture where the ray model of light is used to pictorially represent a light bulb turned off and on. Objects that create their own light have straight lines emanating in all directions from the source. Objects that do not create their own light, or that are turned off, do not have such rays. These student-generated images serve as an excellent jumping-off point for discussing models, which provides the necessary explicit instruction and reflection. Does the sun actually look like this? Do we see individual little rays coming off of its surface? No, but light itself is impossible to draw since it isn't like regular stuff. Students have built a way to understand the world around them, and specifically an aspect of the world that has no observable exemplar. The learner is making sense of the physical world through a model, and the model is built of useful experiences they already possess.

Sense-making in the humanities: theoretical frameworks

Let us now briefly look at an example of sense-making in the humanities, specifically the theoretical framework in historical analysis. As mentioned earlier in this paper, effective history learning should go beyond simply knowing what happened in the past.[16] An understanding of history requires analysis of why events happened and the context surrounding those events. Similar to the science classroom discussed above, the history classroom should be an environment where learners develop an understanding of history by doing historical analysis in a manner consistent with the way the expert historian analyses history: a cognitive apprenticeship.[17]

16 M.T. Downey and L.S. Levstik, 'Teaching and Learning History', in Handbook of Research on Social Studies Teaching and Learning, ed. J.P. Shaver (New York, 1991), 400–10; H. Johnson, Teaching of History in Elementary and Secondary Schools, with Application to Allied Studies, rev. ed. (New York, 1940).

17 J. Brophy, 'Teaching Social Studies for Understanding and Higher-order Applications', Elementary School Journal, 90 (1990), 351–417.

Similar to the model discussed above in science, theoretical frameworks provide a perspective through which to examine a topic in history. The theoretical framework serves as a model of sorts used by the investigator to craft an argument. It can narrow the research question, and can help historians create hypotheses about the higher-order 'why' questions found in the study of history, for example. Within the practice of history, theoretical frameworks often come from other disciplines, such as economics and the social sciences. For example, students of history could examine slavery in the American south-east from a social, economic, political, or a cultural perspective.

Ultimately, the theoretical framework becomes the 'lens' through which the learner views and interpret the facts. It is one way to make sense of history. I shall not discuss specific examples of teaching history as I have with science, because the teaching of history falls outside my area of expertise. However, there is significant documented research in the area of history education where an approach to teaching for understanding founded on situated cognition and cognitive apprenticeship is beginning to show promise.[18]

Summary: the commonalities between making sense of light and history

There are significant parallels between how students best learn how to make sense of and understand light and history. This paper has discussed the construction of models and frameworks that serve as 'lenses' through which the learner makes sense of the world. In the case of light, students can build a model in their mind that serves as a representation of light, which can be used to make prediction about future behaviour and provide understanding about something not explicitly visible to the naked eye. In the case of historical analysis, the theoretical framework similarly serves as a model in the mind of the learner, which can be used

18 L.S. Levstik, 'Building a Sense of History in a First-grade Class' in Advances in Research on Teaching, Vol. 4, Case Studies of Teaching and Learning in Social Studies, ed. J. Brophy (Greenwich, 1993), 1–31; L. Darling-Hammond, 'The Social Studies Near Century's End: Reconsidering Patterns of Curriculum and Instruction', Review of Research in Education, 20 (1994), 223–54; S.S. Wineburg, 'Probing the Depths of Students' Historical Knowledge', Perspectives: American Historical Association Newsletter, 30 (1992), 18–24.

to make sense of historical events. Note that both the ray model and the theoretical framework are but one means each of discovering our world, offering a singular perspective. As students progress in science, they begin to learn other models for light, such as a wave model, and build more and more sophisticated ways of knowing. Similarly, the economic perspective in historical analysis provides one way to 'see' an event, with many more possible views available. Furthermore, as students progress in their learning, they build a more and more sophisticated understanding of history by recognizing patterns.

The main point of this paper is that there is commonality across the disciplines with respect to sense-making. Situated cognition as a theory of learning is not domain specific. Once you accept that knowing is only one aspect of understanding, then cognitive apprenticeship can become your preferred tool for preparing students to make sense of their world for themselves. The parallels between learning science and learning history, or art, or language are apparent when one steps back to see them. And recognizing these parallels is the learner's first step towards developing a systematic and consistent epistemology that they can use in their own sense-making. Because of this, we should begin addressing in our classrooms the cross-cutting nature of the practices of all learners, so that students can see how what they are doing when analyzing history is not epistemologically dissimilar to their physics class.

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